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~~The above cited~~ grant has been used to support several graduate students and researchers in the area of modeling and simulation. The final report lists these individuals and summarizes their research.

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FINAL REPORT

MATHEMATICAL SCIENCES INSTITUTE

FELLOWSHIP IN PARALLEL

AND

DISTRIBUTED COMPUTING

FINAL REPORT

MATHEMATICAL SCIENCES INSTITUTE

GRANT No. DAAL03-86-G-0021

The above cited grant has been used to support several graduate students and researchers in the area of modeling and simulation. The following section lists these individuals and summarizes their research.

Researchers and Summaries of Results

1. **Balas Natarajan** was the first to receive the Fellowship in June 1986. He completed his Ph.D. in August 1986 and his thesis was entitled "On Moving and Orienting Objects", TR #86-775.

   Many problems arising in the area of robotics are directly or indirectly motion related. In order to analyze such problems, it is necessary to incorporate the dynamics with the geometry in the mathematical formulation. Natarajan's thesis deals with two such problems - motion planning in the presence of uncertainty and the automated design of parts orienters. Although these problems are rather closely related, they require very different formulations and methods of analysis owing to the fact that the physics plays a much greater role in the latter problem.

   With regard to motion planning, Natarajan showed that for a large class of inputs, motion planning for rigid objects in 3-dimensional scenes and robots with uncertainty is reducible to the classical piano movers problem and hence decidable in polynomial time. He also showed that the same problem for robots with damping is PSPACE-hard. Despite uncertainty in velocity, time and position, motion planning for robots without damping is a tractable problem. The addition of damping makes the robot more powerful, but makes motion planning for it intractable. In fact, there is good reason to believe that replacing damping with other sensory modes like vision and force-sensing will alter the complexity of the problem in a similar fashion. A study of motion planning with other sensory modes would be a good extension to this thesis.

With regard to parts orienters, the most important contribution of this thesis is the argument that the problem is difficult to formulate in a general manner and requires analysis on a paradigm-by-paradigm basis. Although three paradigms were presented and analyzed in detail, the paradigms were too simple to be immediately useful. The study was largely an initial attempt at bringing together the necessary ingredients to approach this practical problem from the theoretical viewpoint. Further work along these lines could provide a firm theoretical basis for reasoning about this and other such problems.

2. The fellowship was then reassigned to **Lee A. Barford** who was supported from August 1986 to December 31, 1986, at which time he finished the requirements for his Ph.D. Barford received his Ph.D. in May, 1987.

   The Barford thesis describes a solid modeling system whose principal contribution is a constraint-based graphical editor. The editor allows a solid object to be represented as a set of parts, along with constraints which the parts must satisfy. For example, in designing a chair, the user might constrain four points on the under-surface of the seat to touch the four legs of the chair.

   A constraint solver is the key component to any constraint-based editor; such a solver determines how to "glue" the parts together such that all of the constraints are satisfied. The thesis describes how to best implement the constraint solver (through a minimization technique), and also describes a rigorous method of detecting errors due to under-specification and over-specification in the user-defined constraints.

3. **Alberto Paoluzzi**, a faculty member from the University of Rome, Italy, visited the Modeling and Simulation group for a 6-month period, from July 22, 1986 to January 20, 1987. Half of his support came from the Italian National Research Council and half came from MSI. He conducted research on integration systems, which is summarized in technical report #TR 87-804, "Integration Constraints in Parametric Design of Physical Objects."

4. **Douglas Campbell** received the MSI Fellowship from January, 1987 to December, 1989. His research focused on dynamic bounding of robotic systems that resulted in fundamental, practical methods of guaranteeing robot behavior. Campbell left Cornell in January, 1990 to being employment with Mitre.

5. **James Stewart** received MSI support from September 1988 to May, 1989. Stewart is currently a 4th year graduate student and expects to receive his Ph.D. in June 1991. Under the term of his MSI support, he completed his research on underconstrained robot motion, resulting in a paradigm that allows the programmer to write high-level control programs to generate joint trajectories for complex, high degree of freedom robots.

   Stewart is now developing a method to make computational geometry algorithms more robust. Current algorithms assume perfect, infinite precision, arithmetic and ignore the problems of finite precision arithmetic. Algorithms will fail due to inconsistencies in their data caused by incorrect interpretation of finite-precision data. His research on intersecting polyhedrons revealed some unsolved phenomena that arise even in polygon intersections, a problem which had supposedly been solved. Thus he revisited the problem of intersecting two polygons, a trivial problem with perfect arithmetic and perfect input polygons. His wish was to intersect two such polygons to achieve a maximum number of incidences, but discovered that the problem was NP hard. This surprising result showed that, even in the 2D case, finite-precision intersection is a very difficult problem. He is working on the heuristics to develop an efficient 2D intersection algorithm and will soon extend this work to 3 dimensions. A robust 3D intersection algorithm will have immediate applications in current CAD/DAM geometric modelers.

6. **Allen Back,** originally a Visiting Scientist and later a Research Associate, received MSI support form May to December, 1988. Dr. Back's research focused on the development of highly robust finite precision algorithms for the intersection of curved (quadric) solids. He designed a robust system, called *Quadric*, which can intersect a quadric solid with a plane or quadric halfspace. His algorithms have wide applications within graphics, artificial intelligence, and a broad range of engineering computations. The conversion of imprecise numerical data to discrete logical data can lead to subtle (or major) inconsistencies which will cause the implementation of a "mathematically correct" algorithm to crash or produce incorrect results. By emphasizing consistent reasoning rather than highly accurate numerical analysis, Dr. Back's algorithms for intersecting quadric solids with a plane or quadric surface have proved highly robust.

7. **Suresh Goyal**, a Research Associate, was supported by MSI from September to December, 1989. Dr. Goyal directed his research towards the synthesis of a computer based design, analysis and simulation environment. In the three-month period that he

was funded by MSI, Goyal built a simplified schematic model of an automobile and a bicycle to determine the capabilities needed by a schematic modeler, and to uncover any hidden problems likely to arise. Using *Newton*, (a dynamics simulator that was built by other members of the Modeling and Simulation project) to implement his ideas, he recognized the need to develop second order kinematic constraints between two bodies rolling and slipping against each other, while maintaining point contact in order to accurately simulate certain motions. These necessary constraints, which are essential to simulations involving rolling contacts, were developed and explained in Technical Report #89-1047 entitled, "Second Order Kinematic Constraint Between Two Bodies Rolling and Slipping Against Each Other While Maintaining Point Contact."

Advanced Degrees Earned

1. Balasubramaniam Kausik Natarajan, Ph.D. August, 1986.
2. Lee Barford, Ph.D, May, 1987.

Publications

1. On Moving and Orienting Objects. B. K. Natarajan. Ph.D. Thesis. August, 1986.

2. A Graphical Language-based Editor for Generic Solid Models Represented by Constraints. Lee A. Barford. Ph.D. Thesis, 1987.

3. The Role of Languages, Action, and Perception in Flexible Object Manipulation, *Proceedings of the IEEE Computer Society Workshop on Computer Vision,*. D. Campbell, J. Hopcroft, J. Kearney, and D. Krafft. Dec. 1987, 283-287.

4. Towards Experimental Verification of an Automated Compliant Motion Planner Based on a Geometric Theory of Error Detection and Recovery. Jenning, J., Donald, B., and Campbell, D. ICRA 1989 Proceedings.

5. Guaranteed Robot Actions. D. Campbell. Ph.D. Thesis, in preparation.

6. Using the Newton Simulation System as a Testbed for Control, 3rd IEEE International Symposium on Intelligent Control, Arlington, VA. 1988. J. Cremer and J. Stewart.

7. Algorithmic Control of Walking, IEEE International Conference o Robotics and Automation, 1989. J. Cremer and J. Stewart.

8. The Architecture of Newton, A General-Purpose Dynamics Simulator, IEEE international Conference on Robotics and Automation, 1989. J. Cremer and J. Stewart.

9. Second Order Kinematic Constraint Between Two Bodies Rolling, Twisting and slipping Against Each Other While Maintaining Point Contact. S. Goyal. Tech Repot #89-1043.